Revolutionary Innovations in Piezoelectric Actuators and Transformers at FACE

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Abstract

In the middle 90s, the Face Companies created Face International Corporation to focus R&D efforts on high tech applications in the field of piezoelectric technologies. Since then, the company has developed a portfolio of over 50 US patents and several international Patents. The company is currently commercializing three breakthrough technologies including high deformation Thunder® piezoelectric actuators, High Power Transoner® piezoelectric transformers, a battery-less, wire-less remote control powered by its Lightning® piezo generator. A review of these technologies is presented in this poster display.

I. Introduction. History.

The Face Companies were founded in 1888. During the mid-1900's, the company became general and, later, specialty contractors in commercial and industrial concrete floors and toppings. In the 1980's, Face Construction Technologies introduced the first "do it yourself" floor profile measurement device - the Dipstick®. The Edward W. Face Company is now the world's leading authority in the field of floor profile technology. The Dipstick®, used by contractors, testing labs and government agencies in 27 countries, is now recognized as the instrument of record for floor and pavement profile measurement. Adopted in 1988 by the American Society for Testing & Materials (ASTM), and in 1989 by the ACI (American Concrete Institute) the Face Profile Number System (the "F-Number" System) is now the industry standard. Face consultants have worked on more than 6,000 projects on six continents.

In late 1992, Face International Corporation was created to explore the potential of the Smart Vibration Concept (SVC). Face engineers believed that SVC could drive the water and air from newly poured concrete within seconds, to allow finishing immediately after strike-off. It was through the development of this concrete vibrating system that Face International acquired an exclusive and non-exclusive license from NASA for its piezoelectric actuator and sensor technology now trademarked by Face International as Thunder. Currently, Face International is the major worldwide supplier of Thunder technology with sales to over 200 private sector, university and government agency customers since 1997. Since 1996, Face has been awarded 18 patents related to SVC and Thunder. Face International Corporation operates a central research and development center that continues to "spin-off" operating companies once new technologies are ready for commercialization. This allows focused management and investment in companies largely defined by their target markets

While working with Thunder, Face International scientists invented a revolutionary piezoelectric transformer called Transoner®. The patented Transoner technology has been validated by leading experts at the National Science Foundation Center for Power Electronics and has already demonstrated power capacity more than ten times that of other existing piezoelectric transformers (100 watts vs. 10 watts). Due to the importance of this technology, Face International created Face Electronics, LC, as its subsidiary to concentrate on the Transoner based business. Face Electronics sold its first license in August 1999. The Company has recently created a relationship with Pulse Engineering, a division of Technitrol, Inc., to bring to the market Transoner based products and applications. Both companies are currently discussing business relationship with Asian PZT-suppliers.

Face's spin-off practice of Face has been extended to other business including PulseSwitch Systems, LC, which has been assigned all rights to Lightning, a variation of Thunder designed to use the electrical power generated from the mechanical motion of a Thunder actuator. Its first product is the Lightning Switch, a remote control device that can switch on a light, operate appliances or open a garage door without any batteries or wires. PulseSwitch has entered into an agreement with international entities to set up overseas-based manufacturing companies to produce and sell switches in Europe and Japan. That company expects to start the production of the Lightning product by yearly 2004. Figure 10.4 sketches the Face Companies' business segments.

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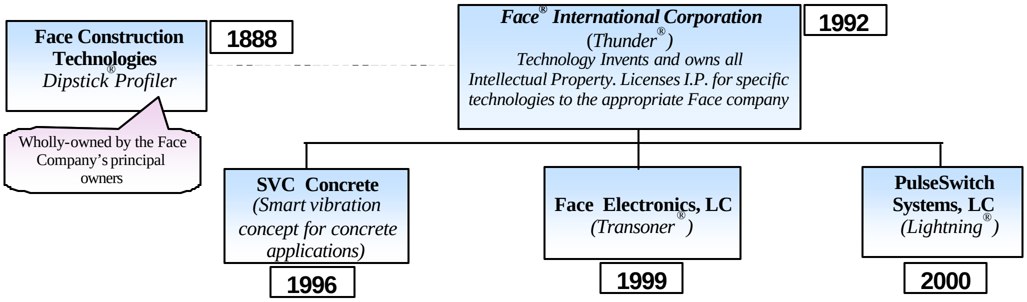

Figure 1. *The Face Companies' business segments*

II. Thunder® Piezoelectric Actuators

II.1. Product Overview

Thunder (THin-layer composite Unimorphs Ferroelectric DrivEr) is a family of rugged, powerful and reliable piezoelectric actuators and sensors initially developed by NASA [1]. These solid state devices are and represent a different class of piezoceramic-based actuators capable of generating significant displacement and force in response to input voltages. This emerging technology has the potential to enable advancements in smart material applications and is currently experiencing exponential growth as an area of smart materials research.

Thunder is a composite structure composed of ferroelectric material intimately bonded using a patented process to one or two metal layers by a high temperature adhesive called LaRC™-SI. LaRC™-SI is a thermoplastic polyimide, developed and patented by NASA's Langley Research Center [2]. In a typical Thunder device, the ferroelectric material is a PZT piezoelectric ceramic wafer that is electroplated on its two opposing faces. A thin steel, stainless steel, beryllium alloy or other metal layer is bonded to an electroplated surface of the PZT wafer by LaRC™-SI and serves as a bottom substrate. A second adhesive layer and, if desired, a second metal layer, typically aluminum or brass foil, is bonded to the opposite face of the PZT wafer as a top layer.

During Thunder manufacturing, the PZT wafer, the adhesive layers, and the metal layers are simultaneously heated to a temperature above the melting point of the adhesive material, and then cooled, thereby re-solidifying and setting the adhesive. While cooling to room temperature, both surfaces of the PZT wafer become compressively stressed, due to the higher coefficients of thermal contraction of the materials in the metal layers as compared to that of the piezoelectric wafer. The result is a 'pre-stress' internal to the individual layers, which deforms the composite structure into a domed shape and gives Thunder its characteristic bow.

The bond between layers is essential because it makes possible the induced pre-stress that results in the distinct advantages Thunder has over other piezoelectric actuators. First, research has shown that this pre-stress enhances displacement performance compared to other unimorph and bimorph actuators and that the effective piezoelectric coefficient (d_{31}) is several times greater in stress-biased Thunder than that observed for conventional piezoelectric ceramics [3,4]. Secondly, this pre-stress keeps the ceramic in compression and allows Thunder to be deflected far more than standard piezoceramics without cracking. Finally, the pre-stress also yields Thunder's unique motion. When subjected to an alternating voltage source, depending on the polarity of the applied voltage, the radius of curvature will either increase or decrease. When sitting as a simple curved beam on a flat surface, this causes the top of the Thunder curve to move up and down with large displacement, creating what has been called a 'pumping motion' (Figure 2).

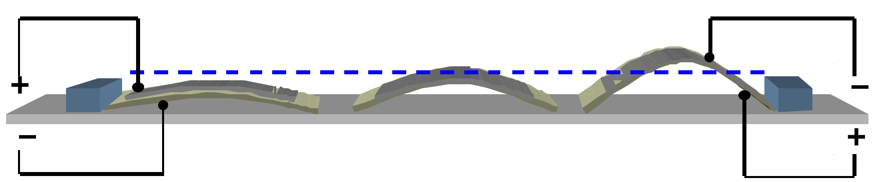

Figure 2. *Thunder motion while simply supported*

The design of the metal layers – the type of material, the number of layers, and layer thickness – can be changed to increase the 'pre-stress' in the ceramic wafer or to strengthen or "ruggedize" the actuator. As a result of this fabrication process, the actuator produced is tough, durable, flexible, robust and highly efficient. Figure 3 summarizes the Thunder manufacturing process

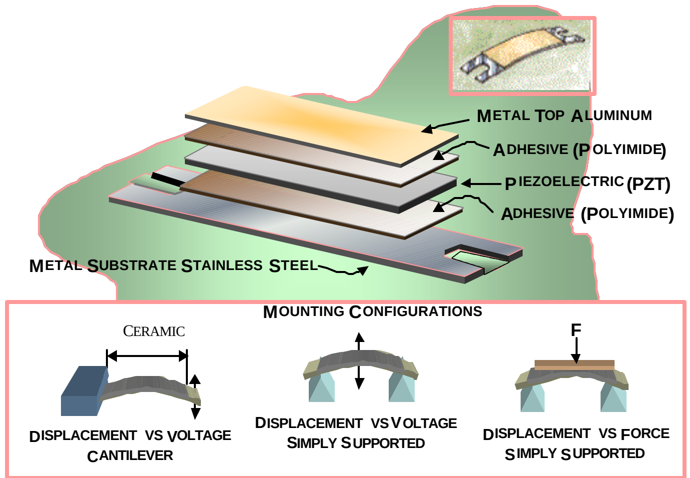

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Figure 3. Thunder parts used during the manufacturing process

Several factors affect the performance of a Thunder device either under load or under no-load conditions. Among the most significant parameters are geometry, number and type of metal layers, thickness ratio of active to inactive layers, mounting system, frequency, and voltage [5]. Because of the many variables that dictate the final performance characteristics of a Thunder actuator, modeling its properties is a complex problem. On the other hand, the large number of variables allows for significant flexibility in design and desired performance. Thunder devices can vary in shape and thickness, which may produce different results depending on the boundary conditions. Common boundary conditions include simply-supported and cantilever mounting designs. The type of mounting conditions will have a significant effect on resonant frequency. The number of layers and type of material play a significant role in Thunder's displacement and force performance.

Curvature is another important characteristic. Depending on the width to length ratio, or thickness to diameter ratio, two modes of curvature can be observed, namely, saddle (*e.g.* curved similar to a potato chip), domed (*e.g.* normally bowed across the length), and sometimes even slightly curved across the width. These shapes produce different performance characteristics and must be considered when integrating the design into an application. The curvature of the Thunder devices has advantages in some applications such as matching of wing or antenna contours.

Thunder actuators and sensors represent a significant advancement in piezoceramic technology. No other actuator in its class exhibits Thunder's mechanical output under load.

Thunder provides inordinately large mechanical output displacements, as high as 30 times the thickness of the device itself. That movement is an order of magnitude greater than other piezoelectric actuators operating in the same frequency range. Thunder actuators can be operated using a broad spectrum of voltage frequencies from dc to kilohertz. These devices lend themselves well to mass production and can be manufactured at a relatively low cost. The fabrication process is readily controllable, resulting in highly uniform production.

Thunder devices can be manufactured in a wide variety of useful configurations – disks, squares, and strips – from a few millimeters to several centimeters in size (Figure 4). Depending upon the application, thickness is nominally less than a millimeter. The simple design, solid-state construction and efficient energy conversion mean that its reliability is high, even under load or pressure. In addition to standard product designs, 'made-to-order' wafers are also available.

These composite piezoelectric structures are extremely tough. The manufacturing process strengthens and protects the basic piezoelectric material with the internal pre-stresses and by the addition of metallic top and bottom layers. Certain models have exceeded 10^8 cycles in life testing under restricted conditions, with no identifiable failures. The metallic layers not only act to protect the ceramic and improve its ruggedness, but also provide a place for electrical connection.

Figure 4. *Typical Thunder shapes and sizes*

II.2. Thunder Applications

Face International has successfully commercialized its line of Thunder piezoelectric wafers, sparking a broad range of potential applications in industry and scientific marketplaces. Applications have ranged from flow control valves to robotic 'bugs' that walk. Table 1 lists specifications for off-the-shelf standard configuration Thunder products.

Table 1. *Standard Thunder Product Performance Characteristics*

Model Number	Overall Dimensions L x W x T (mm)	Resonant Frequency[1] (Hz) (c)	(ss)	Drive Voltage[2] (Vpp)	Typical Displacement[3] (mm)	Block Force[4] (N)
TH-5C	31.75 dia. X 0.480	Not Applicable	532	424	0.13	133
TH-6R	76.20 x 50.80 x 0.787	60	TBD[5]	905	3.12	>133
TH-7R	96.52 x 71.12 x 0.584	31	106	595	7.62	133
TH-8R	63.50 x 12.70 x 0.483	65	177	480	1.98	67
TH-9R	22.35 x 9.65 x 0.533	~3400	TBD	480	0.13	31
TH-10R	25.40 x 12.70 x 0.737	~2800	TBD	480	0.20	36

Notes: [1] Measured in cantilevered (c) or simply supported (ss) mounting. [2] Peak to peak voltage. [3] Measured in a cantilever mount for rectangular pieces and simply supported for the 5C model. [4] Force that restricts motion to 10% of the thickness. [5]To be determined

In this technology, useable mechanical and electrical energy is generated from a lightweight, low power and versatile material. As an actuator, the mechanical deformation of the ceramic can perform work when voltage is applied across its surfaces. This is accomplished by using the motion of the ceramic to vibrate or to move in step increments, depending on the type of input voltage. These movements usually are accomplished by using the actuator as a simple bender or a multilayered stack.

When used in the cantilever position as a bender for applications in the fields of switching, flow control, positioning, or pointing, Thunder actuators are firmly clamped or fastened at one end of the substrate material (Figure 5). Slots can be provided in the substrate for ease of mounting. When used as a simple beam to generate force or create 'pumping motion' for applications in flow control, positioning, vibration damping or on-off control, Thunder actuators should be secured at both ends. One end should be fixed while the other end is free, or more free, to move. Rigidly fixing both ends of the Thunder device in this application will significantly limit the full use of its capabilities. There is also a method to extract work by utilizing the force produced from changes in the effective length of the unit. Additionally, there are several stacking

configurations and changes to basic materials and processes that can be used to modify performance or to magnify certain Thunder characteristics.

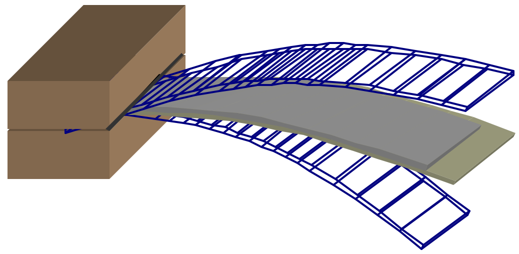


Figure 5. *Cantilever Thunder motion*

Thunder actuators and sensors are being used in a variety of applications and research projects. Businesses, government laboratories and researchers see tremendous potential for such devices. Examples of specific applications being considered and actively researched are given below.

Energy Harvesting

Thunder elements have been integrated into the design of conventional footwear in an attempt to harvest a useful amount of energy 'parasitically' from the weight transfer that occurs during walking [6]. In this application, Thunder was able to generate peak values of 150 volts and 80 milliwatts with net energy transfers of 2 millijoules per step. These values were two to four times that generated by a multilayer laminate of PVDT foil used in the same experiment. A Thunder-based electrical generating system that lasts for two years of average use could produce the equivalent energy of 150 cc of lithium-based batteries.

Precision Positioning

Thunder elements have been integrated into the design of a Self-Contained Actuator (SCA) [7] system used for precision machine tool positioning and chatter suppression, control surfaces on small munitions [8], and a Single Axis Piezoelectric Gimbal [9] used on spacecraft for data gathering instrumentation.

The SCA, designed by Dynamic Structures & Materials, L.L.C, was developed for high speed machining in the automobile industry. The system, built with stacked Thunder actuators, is used for custom profile turning at machine speeds in excess of 10,000 RPM, providing 60-100 lb tool feed force and up to 0.02 inches of stroke control. Singly or in combination, Thunder based actuators can be customized as to size, stroke, force, configuration, material and mounting.

In a recently completed small business research project, QorTek, Inc successfully demonstrated the potential to use Thunder as a flight control surface for miniaturized munitions. Thunder was chosen by the company's researchers because they found it to be more compact and cost less than conventional or grid fin designs while demonstrating superior ruggedness and robustness over other piezoelectric designs.

The piezoceramic gimbal, which can provide rotational motion without the moving parts normally found in conventional designs, has shown promise as a high frequency scanner for sampling or surveillance-type instruments on spacecraft. The gimbal constructed using Thunder was determined to be simple in design, inexpensive to manufacture, had no parts to wear out and was lightweight.

Performance Enhancing Shape Control

Thunder is being investigated for use in changing the shape and geometry of airfoil bodies and space-based antennas. NASA has conducted a feasibility study in which Thunder is incorporated into the upper surface of a sub-scale airfoil [10]. Displacement of the actuator is used to alter the upper surface geometry to enhance performance under aerodynamic loads. Thunder provided up to 13 times the out-of-plane displacement demonstrated by another type of piezoelectric actuator used in the study.

Thunder is also being considered in the design of active reflectors for a space-based satellite aperture antenna [11]. The actuators are designed into the reflector surfaces of the antenna. Displacement of the actuators in a reduced gravity environment will deform the antenna, creating the ability to beam shape and scan without using gimbals or expensive phased

array technology. Changing the shape of the antenna in orbit can improve signal quality without constant reorientation, significantly reducing the number of antennas normally required.

Robotics

Thunder has been integrated into robotic beetles and dragonflies that could be used to gather intelligence [12]. Expendable 'robobugs' carrying small payloads of sensors or cameras could be employed in interplanetary exploration or military situations. Several battery powered robobugs could be deployed on the surface of a planet to make assessments, instead of risking the mission by using only one data collection roving machine. Thunder proved to be beneficial for this application because of its light weight, large displacement, ruggedness and low power consumption. Figure 8 shows some robobugs developed by Center for Intelligent Mechatronics at Vanderbilt University, Nashville, Tennessee, USA under the scope of DARPA (Defense Advanced Research Project Agency) supported project.

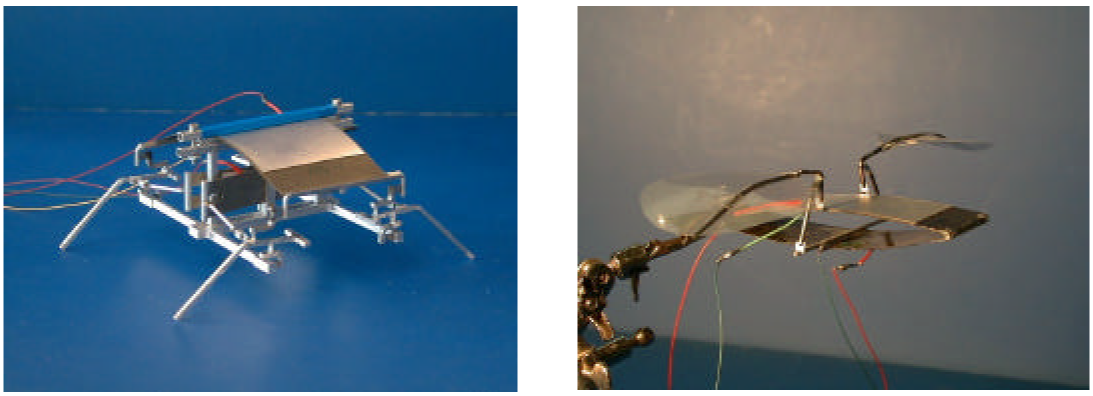


Figure 8. *(Left) Crawling robobug, (Right) Flying robobug*

Active Noise Control

At the University of Delaware, Thunder piezoelectric actuators were used in speakers for active control of noise in aircraft interiors [13]. The benefits Thunder provided in this application were its light-weight and low power consumption. It was especially identified to be superior to other types of piezoelectric actuators because of its ruggedness and reliability.

II.3. Conclusion

Significant progress has been made in recent years in the field of smart materials and structures. Thunder represents one frontier of smart materials research. Additional research is needed before Thunder can be fully utilized as a viable option for applications in a variety of industries.

There are still many challenges in fully utilizing Thunder's potential. More experimental data describing the influence of material selection and geometry on Thunder performance, new modeling techniques, new design methods and new manufacturing processes need to be developed. Research on specific Thunder application performance and boundary conditions is on-going, but is mostly in uncharted territory for this state-of-the-art technology. This includes life cycle testing, environmental testing, new quality control processes, innovative mounting designs, integrated and miniaturized power supplies, performance parameters for customized geometries, effective utilization of Thunder in stacks and clamshell configurations and efficient methods to extract mechanical energy from Thunder movement.

Face International Corporation has made considerable progress towards commercialization. Some customers with realistic expectations and large volume applications are now appearing. The company's client base has doubled in the last year and the number of repeat customers is growing steadily. Meanwhile, some research programs are more than two years old. Utilizing all the advantages of Thunder in real world applications will take time and the concerted effort of smart materials researchers in a variety of disciplines.

III. Transonerâ : New Generation of High Power Piezoelectric Transformers

III.1. Piezoelectric transformers. Approach and historical evolution

Piezoelectric transformers, like magnetic devices, are basically energy converters. A magnetic transformer operates by converting an electrical input to magnetic energy and then reconverting the magnetic energy back to an electrical output. A piezoelectric transformer has an analogous operating mechanism. It converts an electrical input into mechanical energy and subsequently reconverts this mechanical energy back to an electrical output. The mechanical transport causes the transformer to vibrate, similar to quartz crystal operation, although at acoustic frequencies. The resonance associated with this acoustic activity is extraordinarily high; Q factors over 1000 are typical. This transformer action is accomplished by utilizing properties of certain materials and structures.

Piezoelectric transformers were developed in the early 50s by Charles A. Rosen during his PhD work at Syracuse University and documented in his PhD Thesis [22]. Rosen, through General Electric Company, applied for the first patent on piezoelectric transformers on June 29, 1954 getting the final approval on Apr. 8, 1958 [23] (Figure 9). Since then, the evolution of the piezoelectric transformer technology has been closely related to the new demands of electronic devices. High power density, thin profile, high efficiencies, reduced electromagnetic noise, high isolation capabilities, and non-flammability are some of the performance characteristics that have made the piezoelectric transformer the target of many transformer companies.

Piezoelectric transformers are currently on the list of more promising applications for piezoelectric materials. This business opportunity has increased even more in the last few years as researchers realized the possibilities of using piezoelectric devices in power converters. Piezoelectric transformers are currently used in lap top computers and an intense research effort is underway to improve the reliability and performance of the final device including: improvements in the piezoelectric material used, improvements in the mounting system and improvements in the driving circuitry. Transoner® technology, developed in 1998, can play a significant role in this business thanks to its naturally high power performance achieved.

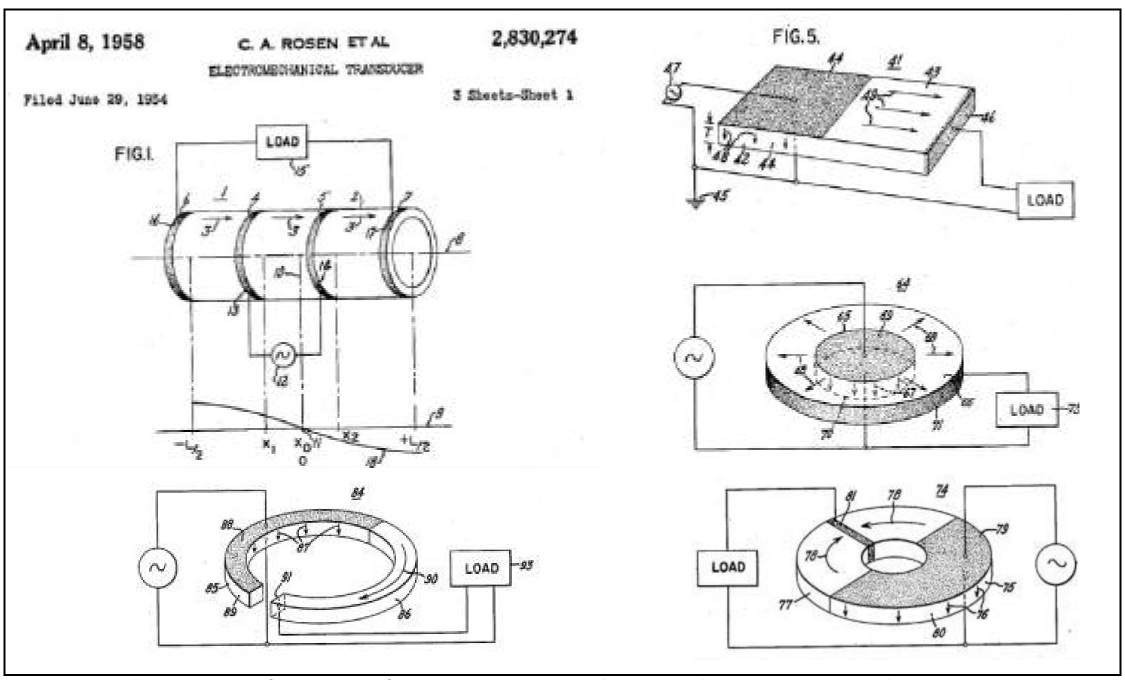


Figure 9. *Piezoelectric transformer configurations proposed in 1958 by C.A.Rosen in the US Patent No. 2,830,274*

During the 70s piezoelectric transformers were considered for the first time as serious candidates for commercial applications. Several US and Japanese companies, including RCA Corporation, Motorola, Denki Onkyo Limited, and Matsushita, considered piezoelectric transformers for generating the high voltage required by the cathode-ray tube in black and white television receivers. In the 80s, Siemens and General Electric, among other companies, worked on the application of piezoelectric transformers for triggering power switch gates such as triacs, tiristors, Mosfets, etc, with galvanic decoupling. However, due to

the incipient state of the technology, including low quality piezoelectric materials and little development in driving circuits, none of the above-mentioned applications had significant success.

In the late 80s, several Japanese companies, including NEC, Matsushita, Tamura, Tokin, made a revision to the concept of piezoelectric transformers, taking advantage of the improvements on novel piezoelectric materials, strategies to drive resonant circuits, and housing solutions. The target of these companies was to develop a low-profile product as an alternative for electromagnetic transformers for customer applications requiring high voltages. Particularly, the main target was to use piezoelectric transformers for backlighting the CCFL (cold cathode fluorescent lamp) for liquid crystal displays (LCD). This application increased the market interest of piezoelectric transformers due to the expansion of lap top computers and other similar portable devices using LCD displays. During the 90s, many patents were issued on modifications of the initial idea of C.A.Rosen, novel driving circuits, mounting solutions, and novel materials to enhance the performance of these devices. Many Japanese lap top companies are using piezoelectric transformers as high voltage devices.

In the early 90s, the focus of many of the companies commercializing piezoelectric transformers was placed on different application environment: power application. However, the existing Rosen-type transformer had obvious technical issues that made this device useless for handling high power density levels. Consequently, an intense research effort has been started to develop novel piezoelectric transformers for power applications in the last years. Face International developed the Transoner concept as a result of their work for improving the laminated piezoelectric actuator Thunder®. The first patent on the laminate piezoelectric design was obtained in 1998. Currently, Transoner piezoelectric technology demonstrates larger power levels in comparison with the rest of the proposed transformer technologies.

III.2. TRANSONER®: Laminated-type Power Piezoelectric Transformer

As mentioned, Rosen-type PTs are currently used in inverters for backlighting the cold-cathode fluorescent lamps in laptop computers, PDAs, digital cameras, camcorders, and other applications using liquid crystal displays. In these applications PTs show significant advantages compared to the magnetic technology, including small footprint, low profile and reduction of magnetic interferences. However, a major drawback of Rosen-PTs is their limited power capability (5 to 10W, typically), and the limitation to only step-up applications. In order to overcome these limitations, Face Electronics developed in 1996 a new concept for transferring energy through acoustic waves by using laminated-type piezoelectric transformers. This technology was patented and registered under the name of Transoner® [2,3].

As in any piezoelectric transformer, Transoner PTs consist of an input section and an output section. These two sections are laminated one over the other one by their major areas. The first Transoners were developed using a radial design consisting of two single piezoelectric ceramic discs (input and output) bonded together in a “laminated-like” way (Figure 10). In this way, when the input section is connected to an AC electric voltage having the frequency of the fundamental radial resonance, the PT will vibrate in the radial direction. Due to the interface area joining both sections, the input vibration forces the output section to move in unison with the input section. Currently, this laminated concept has evolved to designs including multilayers for each section. The multilayer approach allows flexibility in input and output impedance design to be adapted to each specific application.

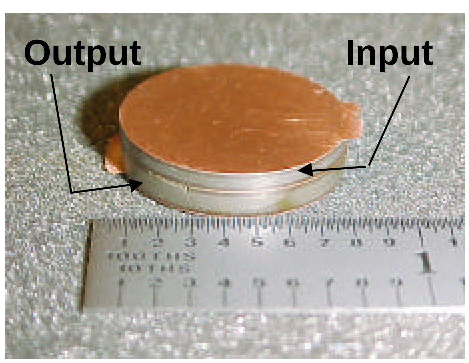


Figure 10. *Radial-type Transoner-T1*

Unlike the Rosen-type PTs, where the input and output sections are separated by a mechanical nodal section, laminated-type piezoelectric transformer, Transoner, input and output section vibrate completely coupled without a nodal section separating

them. Transoner laminated construction enhances the electrical to acoustic power transmission compared to prior Rosen-PTs, due to the use of a larger coupling area. As a result, higher power density levels have been demonstrated in this design. Furthermore, Transoner's laminated flexible design may be adapted to perform step-up or step-down operations, such as the ones used in AC/DC converters, battery chargers, power supplies, and other applications, thus expanding the application possibilities of PTs.

Several types of piezoelectric transformers are currently commercialized by Face to cover both step-up and step-down applications. Step-up applications are typically related to high output voltage and low output current (low power). For these applications, Face has developed a laminated longitudinal piezoelectric transformer. The current design Transoner T-3 delivers up to 10W of power with gains of over 100 when operated with 100kohm loads. In the case of step-down applications, the preferred design is the laminated radial Transoner. Two designs are available from Face Electronics: (a) single input section and single output section design; (b) double input section and single output section design. The second design is best for very high power transfer. Figure 11 illustrates the longitudinal and radial designs.

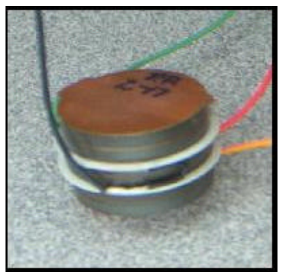
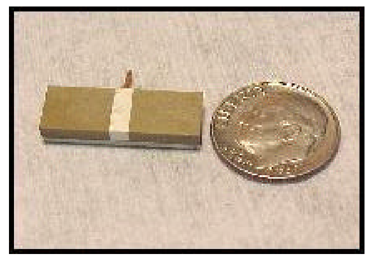
Radial-Type Piezoelectric Transoner		Laminated-Type Piezoelectric Transoner
Single input Transoner T1-type Transoner	Double Input Transoner T6-type Transoner	T3-type Transoner
		

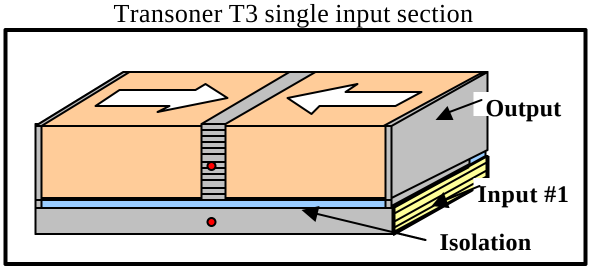
Figure 11. *Different types of Transoner piezoelectric transformers*

III.3. Applications

Step-up applications

Transoner has been integrated into several applications involving high output voltages and low or medium output power. Some of this applications include CCFL inverters for laptop computers (1kV and 5W); CCFL inverters for Flat Panel Displays (1kV and 24W); high power supplies for vacuum tubes such as Traveling Wave Tubes for space-to-earth communications; ignition systems such as igniters for Thrusters for small satellite. For these applications, as mentioned above, the preferred Transoner design is longitudinal. Due to the larger distance between output electrodes, this design allows achieving very larger voltage gain, as required in these applications. Two different designs are currently available for step-up applications, the single input section and the double input section. In both designs the input sections have multi-layer construction to reduce the input impedance as well as increase the gain. The double input section design has been recently developed within the scope of a Phase II NASA SBIR project. This design allows us to increase the power density per unit and provide higher output powers. In both cases, Transoner laminated piezoelectric transformers can provide input to output electrical isolation. Figure 12 sketches both of the standard Transoner longitudinal designs.

Transoner T3 single input section



Transoner T3 double input section

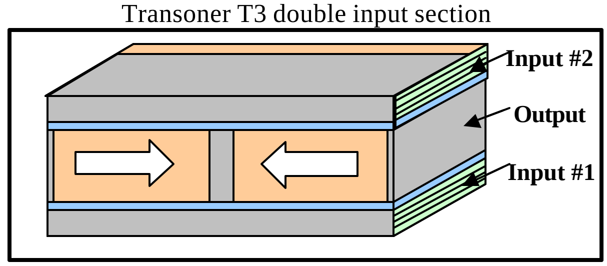


Figure 12. *Longitudinal-type laminated Transoner designs used in high voltage applications*

Step-down applications

Radial type laminated Transoner have been selected worldwide selected as the best approach for power applications. This type of Transoner has been applied to a number of applications including Fluorescent Lamps Ballast, AC-DC and DC-DC converters, wall adapters for AC input, Battery chargers, Power supplies. As illustrated in Figure 12, two types of Transoner designs are available for power applications: the T1-Transoner and the T6-Transoner. T1-Transoner is a single input section Transoner and is recommended for applications up to 15-20W of power. T6-Transoner is a double input section laminated radial Transoner recommended for higher power applications. Face is commercializing the standard T6-Transoner for 50 W applications such as fluorescent ballasts. Figure 13 summarizes the Data Sheet for the standard isolated T6-Transoner. The power density of this Transoner is of 40W/cm^3, which, to our knowledge, is the largest achieved to date from a piezoelectric transformer at these high levels of power.

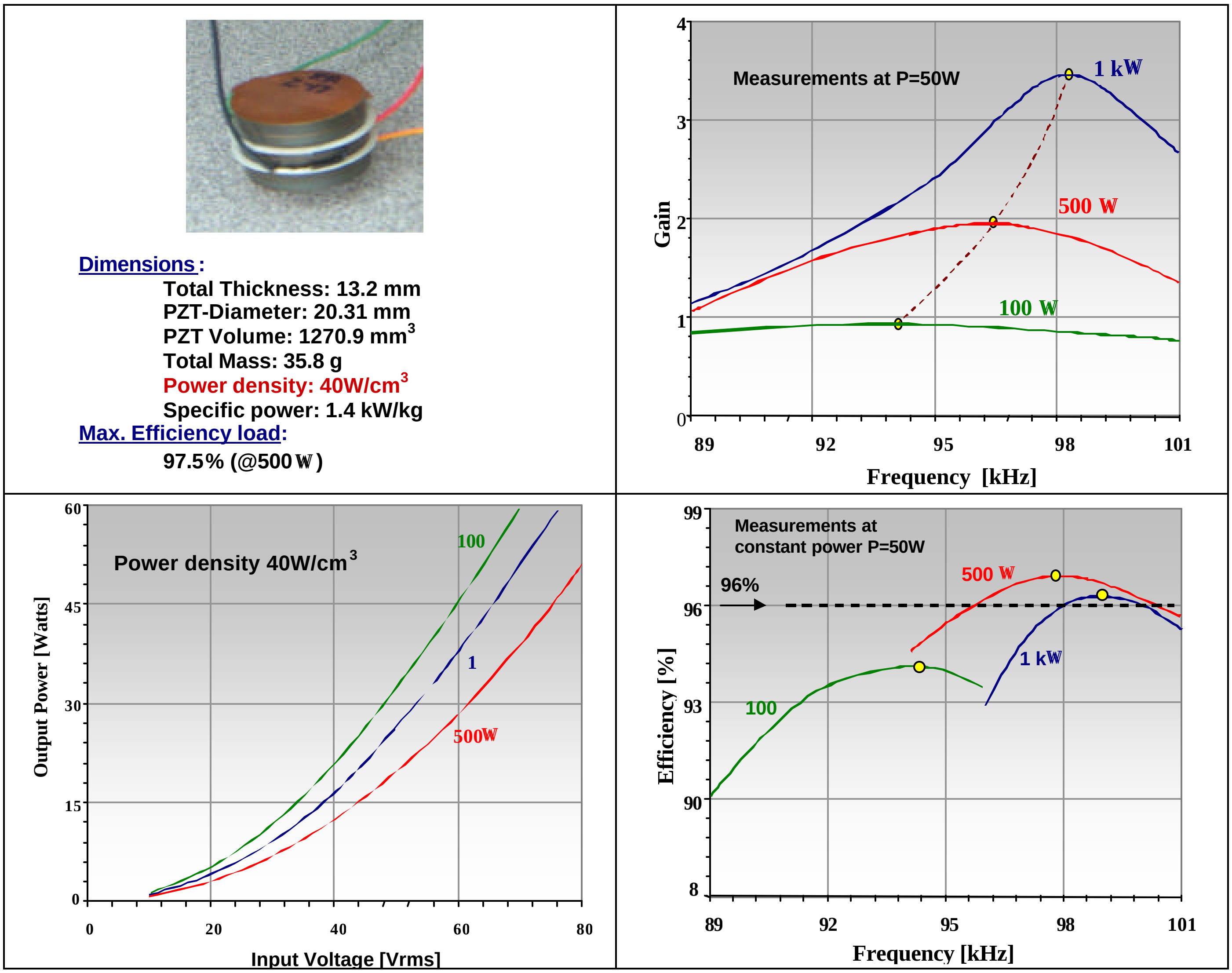
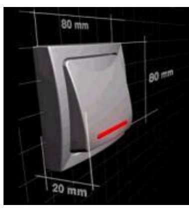


Figure 13. *Datasheet for the standard T6-Transoner isolated.*

IV. Lightning â : Battery-less Power Generators

In the late 1990s, Face International started to consider potential applications for the Thunder actuators in the area of energy harvesting. The initial approach for this work was based on requirements for military applications to harvest energy from soldiers walking in order to recharge the batteries of their GPS positioning devices and other electronic equipment used in the modern military. Based on this need, the company created the Lightning concept. Lightning is basically a Thunder element used as a mechanical to electrical energy converter instead of as an actuator.

The success on this approach made the company consider other applications. Currently, the Lightning piezo element is the heart of the Lightning Switch (known in Europe as the Space-Switch), a battery-less, wireless remote control technology that is to be introduced in Europe (and perhaps in other markets) in Q1 of 2004. The Lightning Switch allows controls for lights and appliances to be installed without wires and without specialized labor, thus saving as much as 50% or more when compared to the cost of traditional wired switch installation.



The Space-Switch

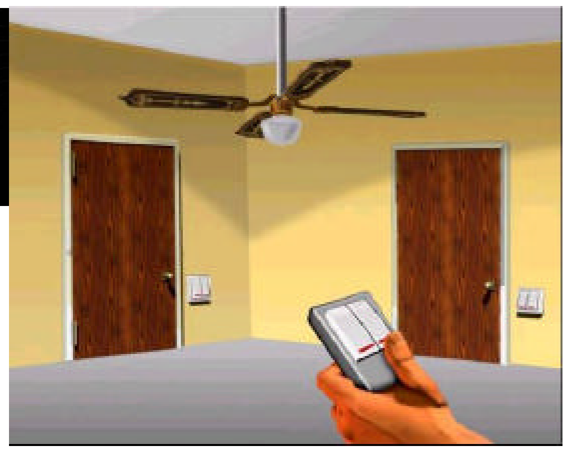


Figure 15. *The Space-switch*

The concept used in the Space-Switch is easy to understand. Mechanical plucking the Lightning element causes the generation of electrical energy. This electrical energy drives a transmitter/encoder system that sends a turn-on/off signal to a receiver that switches on/off a specific home appliance.

VI. References

[1] Thunder® devices are manufactured and sold by Face® International Corporation under licenses from NASA. Thunder devices are protected under US Patent Nos. 5,632,841 and 5,639,850 and other patents pending. Thunder is a registered trademark of Face International.

[2] R. Bryant, "LaRC™-SI: A Soluble Aromatic Polyimide", *High Performance Polymers*, Vol. 8 (No.4), pp. 607-615, December 1996.

[3] R. Schwartz, Y. Moon, "Domain Configuration and Switching Contributions to the Enhanced Performance of Rainbow Actuators," SPIE Proceedings on Smart Materials and Structures, March 2001.

[4] R. Schwartz, Y. Moon, P. Laoratanakul, W. Nothwang, J. Ballato, A. Jackson, "Understanding Mechanics and Stress Effects in Rainbow and Thunder Stress-Biased Actuators," SPIE Proceedings on Smart Materials and Structures, March 2000.

[5] K. Mossi, R. Bishop, "Characterization of Different Types of High Performance Thunder Actuators," SPIE 6th Annual International Symposium on Smart Structures and Materials, March 1999.

[6] J. Kymissis, C. Kendall, J. Paradis o, N. Gershenfeld, “Parasitic Power Harvesting in Shoes,” *Physics and Media Group*, Massachusetts Institute of Technology Media Laboratory, August 1998.

[7] Dynamic Structures & Materials, L.L.C. www.dynamic-structures.com

[8] SBIR Proposal #F001-1784 Topic # AF00-185, “Piezoelectrically Activated Thunder Control Surfaces for Miniaturized Munitions,” QorTek, Inc., Williamsport, PA, January 2000.

[9] G. Horner and B. Taleghani, “Single Axis Piezoceramic Gimbal,“ NASA Langley Research Center, Hampton, VA, 1998.

[10] J. Pinkerton and R. Moses, “Feasibility Study to Control Airfoil Shape Using Thunder,“ NASA Langley Research Center, Hampton, VA, November 1997.

[11] G. Washington and R. Granger, “Reduced G Testing of a Mechanically Active Reflector for an Active Aperture Antenna,“ Department of Mechanical Engineering, Ohio State University, June1999.

[12] M. Goldfarb, N. Lobontiu, M. Gordon, “Optimized Quadruped Robotic Insect Driven by Elastodynamic Locomotion,” presented at SPIE Intemational Symposium on Smart Structures and Materials, March 1999.

[13] V. Jayachandran, N. Meyer, M. Westervelt,, J. Sun, “Piezoelectrically Driven Speakers for Active Aircraft Interior Noise Suppression,“ Department of Mechanical Engineering, University of Delaware, September 1998.

[14] S.D.Johnson, A.E. Witulski, R.W.Erickson, *Comparison of Resonant Topologies in High-Voltage DC Applications*, IEEE Trans. on Aerospace and Electronic Systems, Vol. 24, No. 3, May 1998.

[15] M.A. Pérez, C. Blanco, M. Rico and F.F. Linera, *A New Topology for High Voltage, High Frequency Transformers*, IEEE INTELEC’90, 1990.

[16] Hansen, J.W., Multiple output supplies must meet TWT demands, Microwaves, **21**, pp. 198, Jul 1982

[17] Brill, Y., Eisner, A., and Osborn, L., The flight Application of a Pulsed Plasma Microthruster. The NOVA satellite, AIAA-82-1956, Nov. 1982.

[18] Cassady, R. J., Willey, M. J., Meckel, N. J., and Blandino, J. J., *Pulsed Plasma Thruster for the New Milenium Space Interferometer Experiment DS-3*, AIAA-98-3326, July 1998.

[19] Benson, S. W., Arrington, L. A, Hoskins, W. A, Meckel, N. J., *Development of a PPT for the E0-1 Spacecraft*, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-99-2276, 20-24 June 1999.

[20] LeDuc, J.R., Bromaghim, D.R., Peterson, T.T., Pencil, E.J., Arrington, L.A., Hoskins, W.A., Meckel, N.J., and Cassady, R.J., *Mission Planning, Harware Development and Ground Testing for the Pulsed Plasma Thruster (PPT) Flight Demonstration on MightySat II.1*, AIAA-97-2779, July 1997.

[21] Burton, R. L., and Turchi, P. J., *Pulsed Plasma Thruster*, Journal of Spacecraft and Rockets, Vol. 14, No. 5, 1998, pp. 716-735

[22] C.A.Rosen, “Ceramic transformers and filters’, Ph.D. Thesis, Syracuse University, 1956.

[23] US2830274, C.A.Rosen, K.A.Fish, H.C.Rothenberg, “Electromechanical transducer”, assigned to General Electric Company.